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PARTICLE BEAMS AT PROTON ACCELERATORS

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This topic reflects the dialog going on at this spring 1974 APS meeting and throughout the country concerning the resources available for high-energy physics research. By discussing particle beams and comparing their properties, it should be possible to shed light on part of the high-energy physics resources here in the United States. In addition we will see how we are connected with and dependent upon similar facilities elsewhere.

When one thinks about high-energy or particle physics, the attention, glamour, and most of the discussion centers upon the sources of the particles; these, of course, are the accelerators. In the early life of any accelerator project there is a controversy (perhaps dialog) about what the energy, intensity, and scope of the facility should be in order to accomplish the current physics goals or at least to take a giant step above what has been available so far. After the device is built, attention shifts to the experiments which are done using it. Some of them are enormous, involving large commitments of manpower and personnel. Others are much more modest, done by one or two people. The forgotten field in this whole endeavor lies between the accelerators and the research, namely the experimental areas. This involves the people and funds that produce the beams, facilities, and resources needed for outstanding research. At most accelerators the funds and effort eventually invested in the experimental areas exceed those which go into the accelerator initially. Because of the large investment, it is instructive to focus one's attention from time to time on these areas and measure their strengths and weaknesses, their scope and influence on the particle physics research program at each laboratory.

Work in experimental areas centers around the problems associated with targeting high energy, high intensity primary proton beams, and the difficulties of collecting and analyzing the streams of particles which emerge from such primary targets. These streams of particles are commonly called secondary beams and in most laboratories are the probes used for studying the strong, electromagnetic, and weak interactions which occur when they strike other particles or detectors. At the end of the beams are the massive detectors such as large bubble chambers, spectrometer arrays, and electronic detectors used for measuring the energies and directions of the particles coming from such interactions.

I have dealt on these almost obvious activities that comprise this intermediate field in order to highlight its existence, to define its range, and to emphasize the important role it plays in making each accelerator's energetic beams useful for particle physics research. In this paper I am going to restrict myself to the experimental facilities associated with three proton accelerators in the United States: the Zero-Gradient Synchrotron (ZGS) at Argonne National Laboratory, the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory, and the Proton Synchrotron at Fermi National Accelerator Laboratory (Fermilab). How these accelerators compare with respect to energy and intensity is shown in Table I.

Table I. Comparison of Accelerator Energy and Intensity.

	ANL	BNL	Fermilab
Energy - Typical (GeV)	12.5	28.5	300
Intensity ($\times 10^{12}$ proton/sec)	0.9	2.5	2.0
Primary target locations operational	11	8	7
Detector stations available for use	13	12	17
External detector stations operating simultaneously	8	7	9
Counter experiments in external stations operating simultaneously	7	6	8
Bubble chamber operating stations operating simultaneously	1	1	1

At this point, we should consider yet another parameter, duty cycle. These proton accelerators are pulsed devices. Consequently, they provide a stream of particles for some fraction of the time on every cycle. At Fermilab this is 1 second out of nearly every 7 seconds, or a duty factor of about 15%. Some are as brief as 1 second of every 3, a 33% duty factor. The duty factor, although low when one considers using the beam at peak energy, can be considerably extended whenever it is possible to use the circulating proton beam during acceleration, as shown in Fig. 1. One can see how the duty factor has been increased by a factor of three to four, to 60% or so, by stretching out to approximately 4 seconds the use of the circulating beam.

Now technically I have strayed a bit from the discussion of particle beams by mentioning the circulating proton beam. That beam is captive within the accelerator vacuum system and not easily available. Nevertheless, at Fermilab when acceleration was first achieved, the circulating beam provided the earliest opportunity for direct study of proton collisions. Currently, the circulating beam of 10^{13} protons, when caused to collide with hydrogen in the jet target, has an interaction rate of 10^{9} per second. This rate is equivalent to that which would be realized with an external proton beam of 10^{10} protons per second incident upon a 2-foot-long hydrogen target.

Internal areas play the strongest role in the beginning operation of a new accelerator. For example, at the Brookhaven AGS the internal target was used in two locations, F10 and G10, to initiate experiments at that facility. The targets were plunged into the beam when it was near its peak energy. Secondary beams were initially produced from such targets for Brookhaven and Argonne as their experimental programs developed. Secondary beams originating from targets within the accelerator itself must be highly reliable. Any failure of components within the accelerator's primary shield can cause a shutdown of the entire research facility. Consequently, internal targets are not highly favored once external beams are available. At Fermilab we have decided not to produce secondary beams from internal targets, and, consequently, use them only for specific types of experiments.

The full flowering of the use of proton accelerators comes with the extracted beam. When the beam is removed from the confines of the accelerator it can be handled in an efficient manner and made to produce a number of secondary beams. Extraction can be accomplished in many different ways, some more efficient than others. The most efficient, nearly 100%, is when the beam is yanked out of the accelerator in one sharp motion. This is called fast extraction, and in the limit its beam duration is the revolution time of the protons within the accelerator. At Fermilab this corresponds to about 20 μsec of beam. For most purposes that is just too short an impulse, and it is much more satisfactory to bring the beam out in a "slow" manner. Using resonant extraction, the Brookhaven and Argonne beams are provided into their respective experimental halls 1 second out of every 3 or 4 seconds. The beam can be slowly extracted with an efficiency approaching 95%, with the losses dependent upon the physical size of the extraction devices.

When the proton beam is free of the accelerator it is usually focused down to a small spot and targeted on particle production targets. Spot sizes are an important consideration for the production of high resolution secondary beams. Typical spot sizes range from 0.5 cm to 0.5 mm for the accelerators about which I have been speaking. The slow extraction process actually shaves off a portion of the circulating beam's phase space; consequently, the spot size of a proton beam when slowly extracted is smaller than it is when fast-extracted.

With the small emittance (at Fermilab, $E_H = 0.1$ mm-mrad) goes either a small spot size, or a small divergence, or both, under very favorable conditions. This is another advantage that arises from going to high energy--as the energy gets higher and higher the actual transverse excursions of the beam are greatly reduced, leading to a more concentrated spot of protons. The concentrated source creates great practical problems of materials engineering. Proton beams presently available contain tens of kilowatts of beam power and in fact readily warp and sometimes melt targets that are inadequately cooled. At Fermilab energies another phenomenon takes over which plays a very important role in the beam design. Mesons and kaons produced from these collisions in the target decay into muons and neutrinos. Both of these particles are very penetrating and cannot be contained within the typical beam dump. In fact, in the >100-GeV regime the most important shielding problems are related to getting rid of the muons. This is accomplished by ranging the muons out in dense material by ionization loss. Typically it takes a meter of iron to lose 1 GeV of energy, so one can easily see why the 1-km secondary beam lines at Fermilab and in the emerging plans for CERN II are so long.

The major purpose in targeting the high-energy proton beams is to produce more interesting secondary-particle beams. Some comparisons between particle production data that were measured at Fermilab by Meson-Area experimenters and a model calculation of the particle dependence done by C. L. Wang at Brookhaven are shown in Fig. 2. There is really quite good agreement between the parametric theory and the measurements. Another way of looking at this which is independent of energy is to plot the same data against the fraction of the available forward momentum. This is shown in Fig. 3, where these data are replotted. $X = 1$ is the hypothetical upper limit of the 300-GeV secondary beam produced by 300-GeV protons. To turn these curves into practical values, we must say something about acceptance in secondary beams. Acceptance is a combination of the geometrical size of the focusing lenses and the ability of the receiving system to hold the particles within a given energy rnage. Typical solid angles available are 400 μsr at Argonne, 200 μsr at Brookhaven, and 2 μsr at Batavia. The acceptance of beams at higher energy accelerators can be smaller, because the need for high acceptance drops off at the higher energies. This is again the bonus that arises from high-energy accelerators. At high energies the particles are concentrated into more and more of a forward cone. This is usually represented by the expression $p \times \theta \doteqdot 300$ MeV/c, transverse momentum is nearly a constant independent of the energy of the initial particle. Consequently, particles of higher energy (p) tend to come off at smaller angles (θ). These smaller angles can be accepted into focusing lenses of appropriately smaller size. Consequently, quadrupole magnets with 8-inch diameters which are used at Argonne and Brookhaven energies become 3 inches in diameter at Batavia energies. Let me put down some practical values for the production and acceptance of secondary beams at Fermilab in order to see what sort of flux one gets. A secondary beam of 1 μsr and a momentum acceptance of $\pm 0.1\%$ $\Delta p/p$ yields a particle flux of 2×10^5 π^- per second at $x = 0.33$ or 100 GeV/c. As one goes out to larger angles the flux of particles falls off and consequently to produce practical beams there must be a clustering of these separate channels around the forward direction. Typically, it is possible to have as many as four or five secondary beams from one target, although at the higher energies fewer beams are more efficient.

There are many different kinds of secondary beams, charged, neutral, penetrating, electromagnetic, etc. Perhaps a way to first get an overview of this is to look at the different types of beams available at the three laboratories. Five major categories of secondary beams and my enumeration of the number of these beams that exist at each laboratory are listed in Table II. This table categorizes the major properties of beams, whether charged, neutral, or special beams, and whether they are for general purpose use or for a fixed facility. The most sophisticated beams are the separated beams. As such, they

Table II. Secondary Beams.

	ANL	BNL	Fermilab
Separated charged beams for general use	2	$3\frac{1}{2}$	0
Separated charged beams for fixed facilities	$1\frac{1}{2}$	$2\frac{1}{2}$	0
Unseparated charged beams for general use	4	2	3
Unseparated charged beams for fixed facilities	1	0	$1\frac{1}{2}$
Neutral beams for general use	2	3	$2\frac{1}{2}$
Neutral beams for fixed facilities	$1\frac{1}{2}$	1	2
Special purpose beams for general use	0	2	0
Special purpose beams for fixed facilities	0	0	1
Extracted proton beam for general use	2	0	3
Extracted beam for fixed facilities	0	0	0
	14	14	13

Beam Sources

	ANL	BNL	Fermilab
Beams from internal target	2	4	0
Beams from external target	11	9	12
	13	13	12

are a valuable part of the resources available at the older accelerators, while unseparated charged beams and neutral beams for general use are an important part of the life of a new accelerator.

The ISR is a very important step into the highest energy regime. It provides in proton-proton collisions, the maximum possible chance for the penetrating interaction of protons. An intersecting storage ring does not provide, however, for the copious production of pions, kaons, neutrons, neutrinos, muons, etc., that create a broad illumination of particle physics phenomenon. That can only be done by a conventional (or not so conventional) fixed-target accelerator.

In the spirit of an overview of the beam resources available in the country, one should consider beam economics. Generally speaking there is an optimum region of secondary momentum coverage for particle beams. In the units that we used before, the coverage is from about X = 0.1 to X = 0.5. This is illustrated in Fig. 4 where I have drawn lines representing the energy coverage of the popular unseparated, charged beams that exist at the three laboratories. This graph indicates that we have far from full coverage between the low energies and the very high energies. It does show, however, how attractive it is to have a ~100-GeV accelerator providing beams for physics research in the United States, particularly when Fermilab energy reaches 1000 GeV. Of course, this is the general region (~76 GeV) covered by the Serpukhov accelerator in the USSR forming an important bridge in the gap between ANL and Fermilab energies as well as between nations.

The question of the optimum energy coverage is more than academic, and plays a role in making the most effective use of beams for experiments. There is very little point in using the resource of a very high energy accelerator to produce low energy beams. The electrical power used in producing the higher energy is dissipated in heat and target destruction to provide low energy particles. I feel that whenever possible accelerators should be used at near their peak energy. This provides a strong role for each accelerator to fill. In addition, to have a full national program, one should have a source of particles throughout the 1000-GeV range in order to make the full sweep of the energy region from 1 to 1000 GeV.

One must also discuss the multiple use of beams. In some cases the secondary beam particles are not used up through the first or second detectors. The most obvious example of this are neutrino beams which can be used many times in the course of experiments. Other beams can be effectively used by splitting such that particles can be supplied to two separate beam channels simultaneously, or if all else fails, switched over from a channel where they are not being used to another. Such arguments call for the careful design of secondary beams channels and the use of those beams in the optimum energy region at all times.

This leads me into a natural discussion about detector stations, which are a measure of the multiple use that can be made of secondary beams. Both Brookhaven and Argonne have made extensive use of branches for multiple experimental setups. A rough count of those possibilities was shown in Table I. The plans for Fermilab, shown in the third column, are predicated upon the primary proton beam and targeting facilities that have been designed into the accelerator and experimental areas so far. In each case the number of detector stations per beam line is a measure of the flexibility that exists to be exploited through research program planning.

Finally I would like to turn to the question of throughput. By this I mean the number of experiments accomplished per year. With flexible beams, the experimenters can be intermittent in their use of the beam such that each beam is used by several experimental groups during the course of the year. Throughput is a measure of research productivity and is proportional to the number of detector stations, the duration of the experiment, and available operating funds. The throughput available from any given accelerator facility is a quantitative measure of the research capacity, both of the facility and of the groups using it.

Today, Argonne, Brookhaven, and Fermilab play the major role in the amount of research work done using hadronic beams. A healthy national research program would result from the operation of each of these facilities at nearly full capacity, providing experimental opportunities for researchers. These accelerator laboratories cover unique energy regions, and they must do so in an optimized way, making it possible for a large number of experiments to be completed per year. This will provide the most favorable return that can be made from our national investment in high energy research facilities.

Having generally discussed the coverage of secondary beams, let me now illustrate this by speaking about the specific beams that exist at Fermilab. These are the beams with which I'm most familiar, as well as the ones which are new to the physics community.

Let me start by discussing the ordinary secondary beams that exist most clearly in the Meson Area. This area is found to the left of the extracted beam in Fig. 5. As shown in Fig. 6, downstream from the target are five secondary beams: three for charged particles and two for neutral particles. The overall properties of these beams are shown in Table III.

Let me interrupt my description of the beams to point out an obvious result that we find in the use of this area. The Meson Area was originally designed for 200-GeV protons. As such it could not supply pions at 200 GeV under any conditions. Now that we regularly operate at 300 GeV, it has a handsome flux of 200-GeV pions. This is one of the finest examples that we have of the quantitative benefit of high energy.

Turning next to the Neutrino Area we see the first examples of the very specialized beams that have been built in the multiple-hundred GeV accelerators. The dominant example is the neutrino beam which has determined the characteristics of this area. The decay pipe must be followed by a filter to remove the muons. For 400-GeV operation this has led to a decay distance of 1300 ft and a filter of 3000 ft. We have used earth shielding for the filter so that it can be changed to ordinary or magnetized iron in the future to make a 1000-GeV area.

Some muons are swept to the side and eventually compose the collimated beam of muons that go on the Muon Area. In parallel with this, a low intensity hadron beam by-passes all these elements to provide an unseparated hadron beam for either the 30-inch or 15-foot bubble chamber. The properties of the Neutrino Area beams are outlined in Table IV.

Table III. Meson Area Beams.

Beam Line	Production Angle (mrad)	Maximum Momentum (GeV/c)	Solid Angle (μsr)	Momentum Acceptance (Δp/p)	Approx. Flux per 10^{13} Interacting Protons at 300 GeV
M1 High energy, medium resolution beam	3.91	200	2.0	±0.1%→±2.0%	10^7 π at 150 GeV
M2 Diffracted proton beam	1.75	300	0.22	±0.1%→±1.4	10^{10} p at 200 GeV
M3 Neutron beam	1.75	-	Variable	-	$10^8/cm^2$
M4 K^0 beam	6.5	-	Variable	-	$10^6/cm^2$
M5 Test beam	20.0	40	6.2	±0.05%→±0.5%	10^6 π at 50 GeV
M6 High energy, high resolution beam	3.05	200	1.34	±0.014%→1.0%	10^7 π at 100 GeV

Table IV. Neutrino Area Beams.

Beam Line	Production Angle mrad	Maximum Momentum GeV/c	Solid Angle μsr	Momentum Acceptance $\Delta p/p$	Approx. Flux per 10^{13} Interacting Protons at 300 GeV
NO-1 Quadrupole, narrow-band neutrino beam	0	300[a] 200[b]	4 - 16	±5%	10^6 Neutrino through 1 m^2
NO-2 Broad band, horn focus neutrino beam	0	500	2800	5-500 GeV	10^{10} Neutrino through 15-ft bubble chamber spectrum peak at 20 GeV
N1 Muon beam	0	200		±2%	10^6 μ^+ at 150 GeV/c
N3 Hadron beam for 30-in. bubble chamber	Variable $0 \le p_T \le 1$ GeV/c	500	0.3	±0.07%→±1.2%	Sufficient for bubble chamber
N5 Hadron beam for 15-ft bubble chamber	Variable $0 \le p_T \le 1$ GeV/c	500	0.3	±0.02%→0.6%	Sufficient for bubble chamber

[a] On target.

[b] Secondary.

The Proton Area is a modern-day version of an internal target area, except that the extracted proton beam is brought out to be used directly in proton heavy target collisions. In these dense collisions we look for unusual events involving large momentum transfer. Other interactions exploit the special symmetries of proton-proton collisions. Such reactions will be studied extensively in the next few years. In time the Proton Area will serve as a source of yet higher energy secondary particles to be formed into beams to new generations of detectors.

Turning back to other laboratories, we have just heard about a unique property of some ANL beams. The polarized proton capability is a good feature of the weak-focusing synchrotron, and a property that is most important at lower energies. Another example that must be highlighted at this time are the low energy or stopping K beams that exist at ANL and BNL. These remarkable beams offer the capability of stopping 10^5 K's per pulse into nuclear targets. The separated beams which exist at ANL and BNL are a major resource, particularly when directed into fixed facilities such as multiparticle spectrometers. I assure you that it is not possible to create such beams at Fermilab. The regimes of unique physics capability are remarkably different and need to be exploited. Increased mobility of research groups seeking the best beams are called for rather than an undesirable and not quite workable concentration of beams at one facility.

Rather than trying to compare the proton beams at the different accelerator facilities, let me emphasize the importance of overlap. The energies of the secondary beams should be determined primarily by the energy of the accelerator. Whenever high intensity is available, the secondary beams should be sized to operate from 10 to 75% of the peak energies as far as most secondary particles are concerned. Of course, diffracted proton and neutron beams go up to the maximum energy. Beams that involve diffracted protons have the highest intensities available and are typically about a million times more intense than the most intense secondary beams. They must be shielded and operated with extreme care.

From a proton accelerator it is possible to produce both electron and muon beams, and from time to time the controversy rages as to which of these is more important. There is no simple answer to this question, and we find that both types of beam play a role in the experimental program. It is clear that both will persist until it is understood why the electron and muon are so alike and yet differ in mass.

In conclusion, let me suggest that creative thought be given to developing the maximum utilization of all the accelerated protons. To maintain our momentum in the face of the tight budgets, we must achieve higher productivity and cost consciousness. Finally, a delicate balance must be set between the accelerator and the detector facilities. It is our job to maintain this balance, and take pride in this rich national resource.

FIGURE CAPTIONS

Fig. 1. Energy and intensity cycles in the Fermilab accelerator.

Fig. 2. Particle production data measured by Meson Area experimenters, compared with a model calculation of the particle dependence done by C. L. Wang.

Fig. 3. The data of Fig. 2, replotted against the fraction of the available forward momentum.

Fig. 4. Energy ranges of the general purpose secondary beams at ANL, BNL, and Batavia accelerators.

Fig. 5. Diagram of the Fermilab site.

Fig. 6. Diagram showing the experimental beams available at Fermilab in spring 1974.

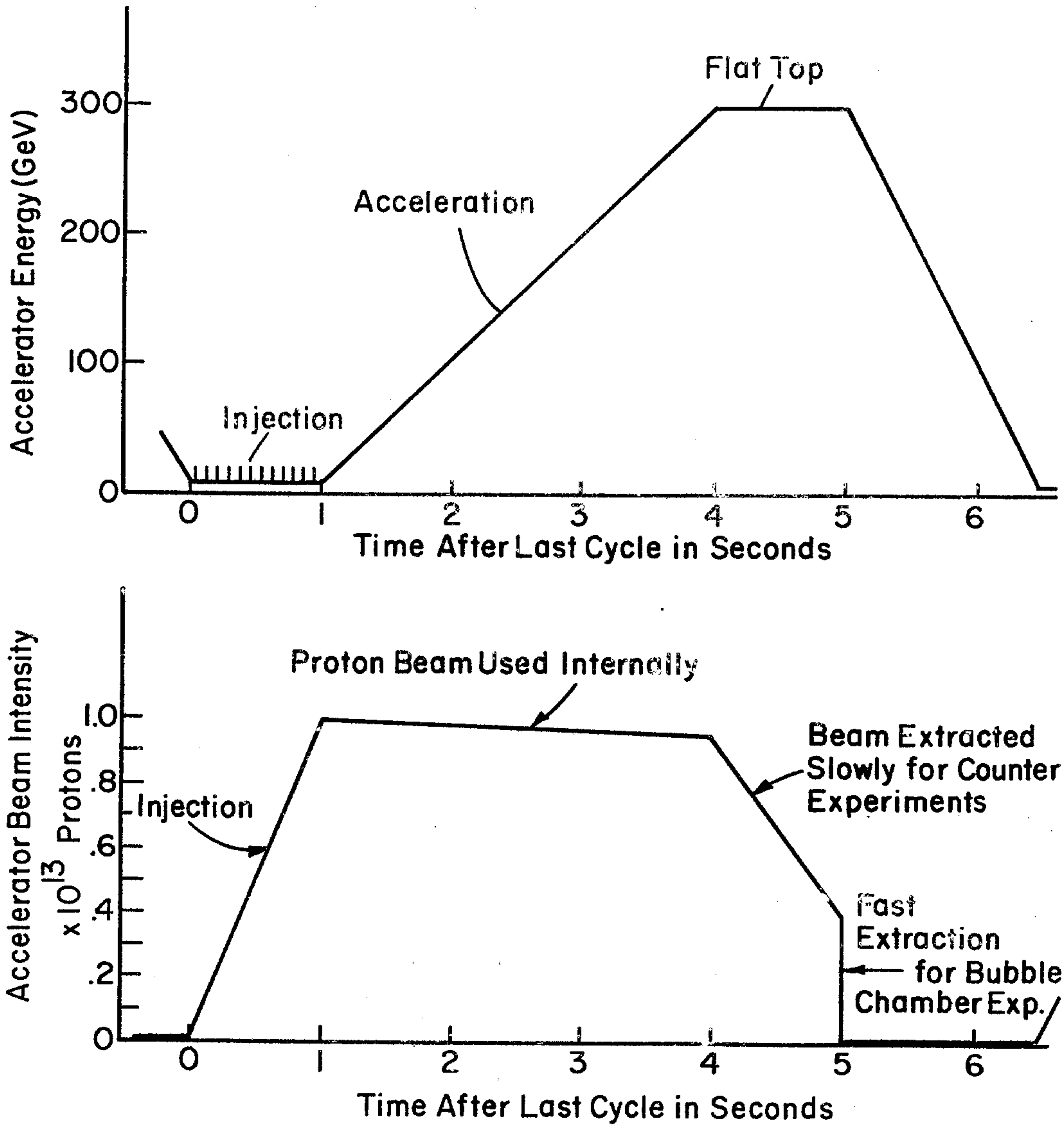
Flat Top
Acceleration
Injection
Accelerator Energy (GeV)
300
200
100
0
0
1
2
3
4
5
6
Time After Last Cycle in Seconds
Proton Beam Used Internally
Beam Extracted Slowly for Counter Experiments
Injection
Fast Extraction for Bubble Chamber Exp.
Accelerator Beam Intensity x 10^13 Protons
1.0
.8
.6
.4
.2
0
0
1
2
3
4
5
6
Time After Last Cycle in Seconds

Fig. 1

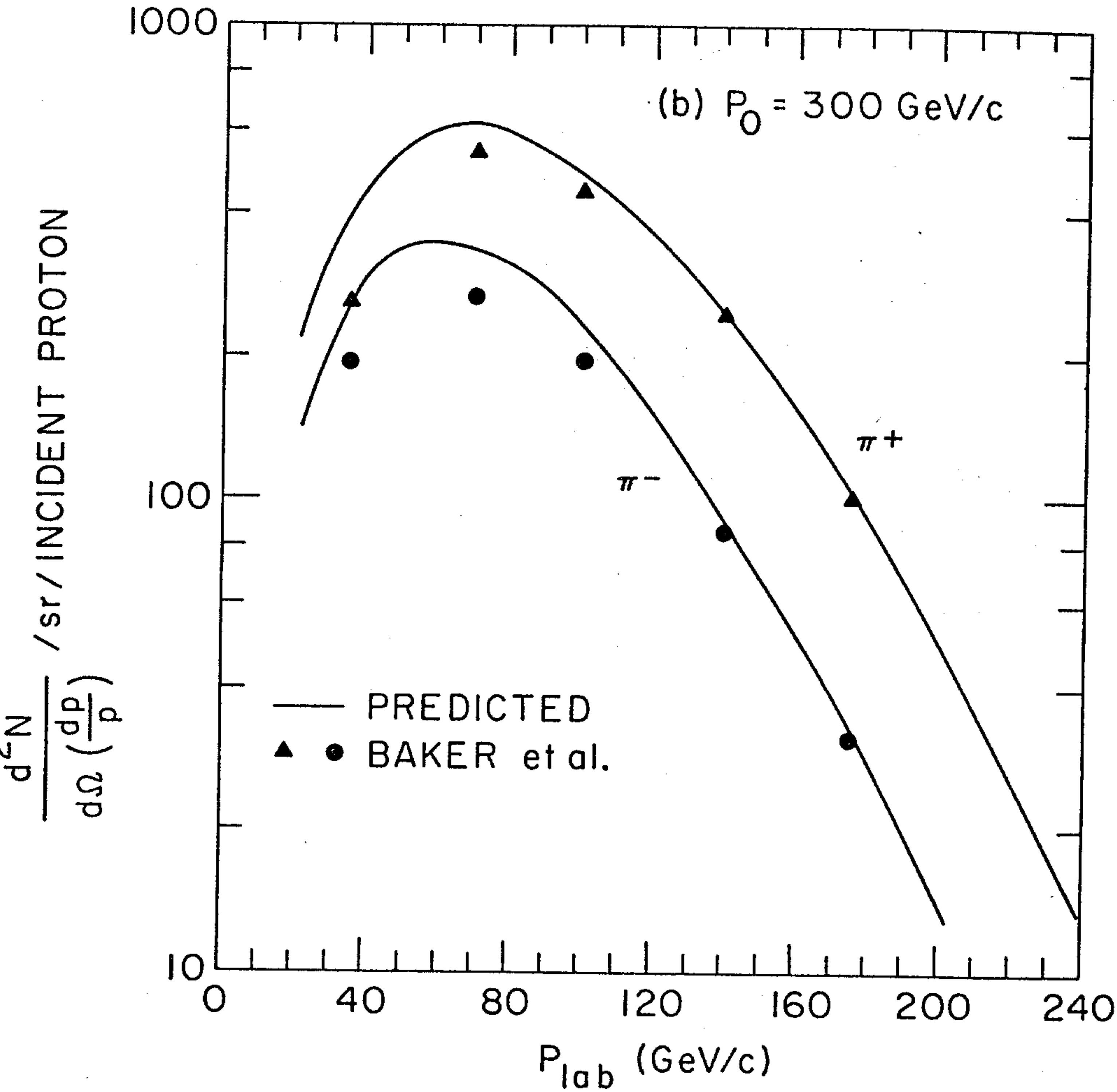
(b) P_0 = 300 GeV/c
$\frac{d^2N}{d\Omega\left(\frac{dp}{p}\right)}$ /sr/INCIDENT PROTON
1000
100
10
0
40
80
120
160
200
240
P_{lab} (GeV/c)
π^+
π^-
PREDICTED
BAKER et al.

Fig. 2

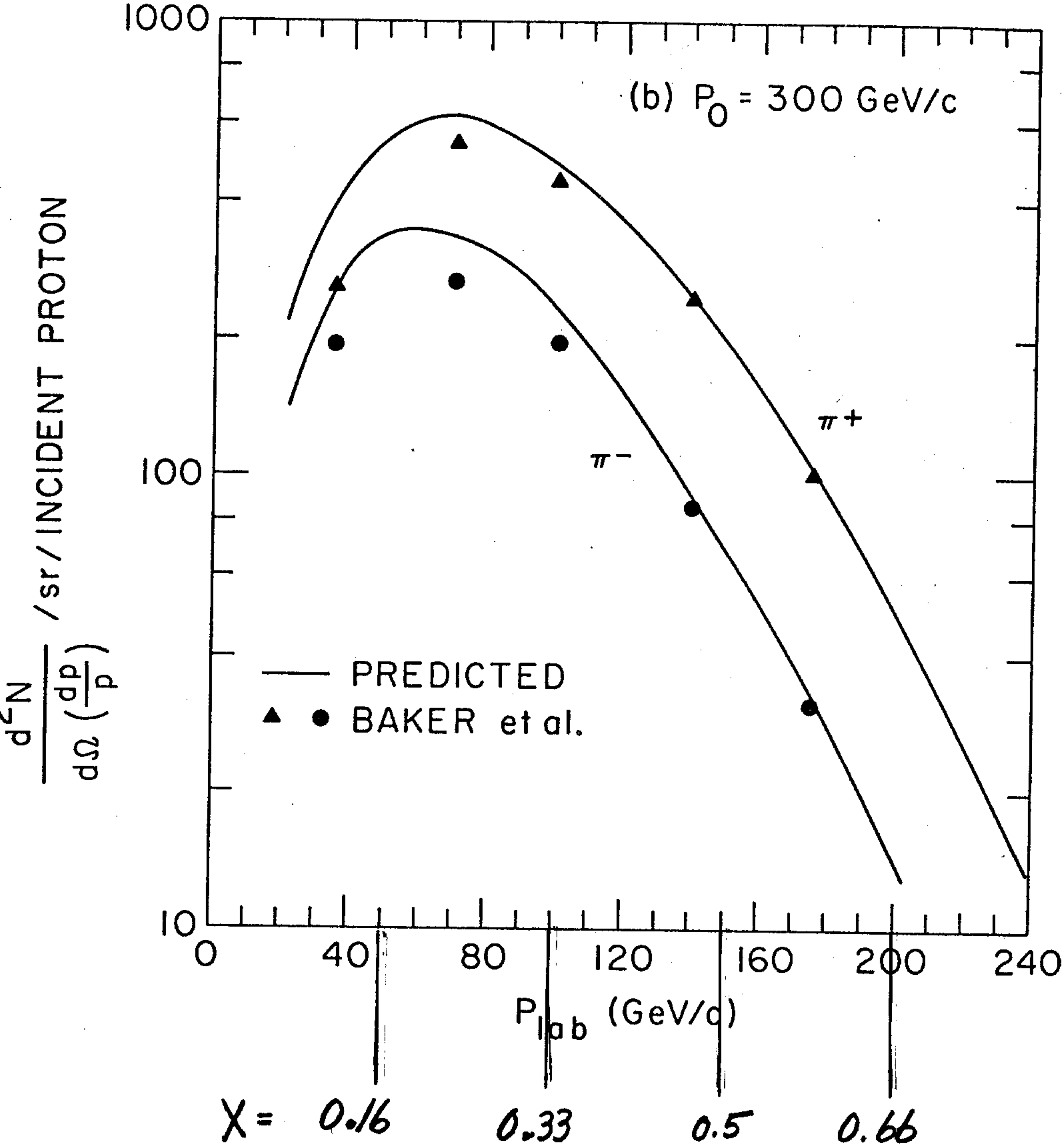
(b) P_0 = 300 GeV/c
$\frac{d^2N}{d\Omega\,(\frac{dp}{p})}$ /sr/INCIDENT PROTON
1000
100
10
0
40
80
120
160
200
240
P_{lab} (GeV/c)
π^+
π^-
PREDICTED
BAKER et al.
X = 0.16
0.33
0.5
0.66

Fig. 3

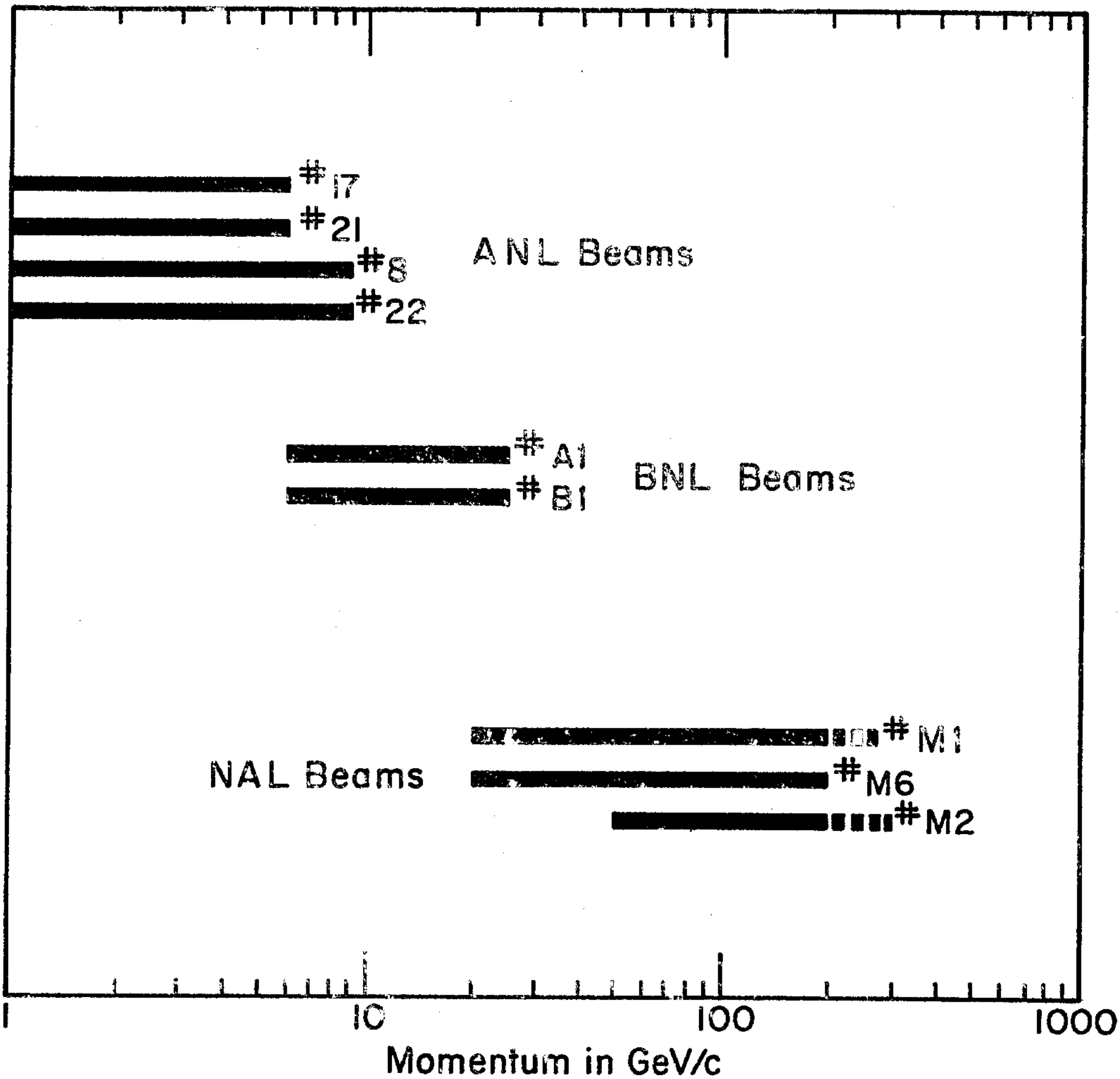
#17
#21
#8
#22
ANL Beams
#A1
#B1
BNL Beams
#M1
#M6
#M2
NAL Beams
1
10
100
1000
Momentum in GeV/c

Fig. 4

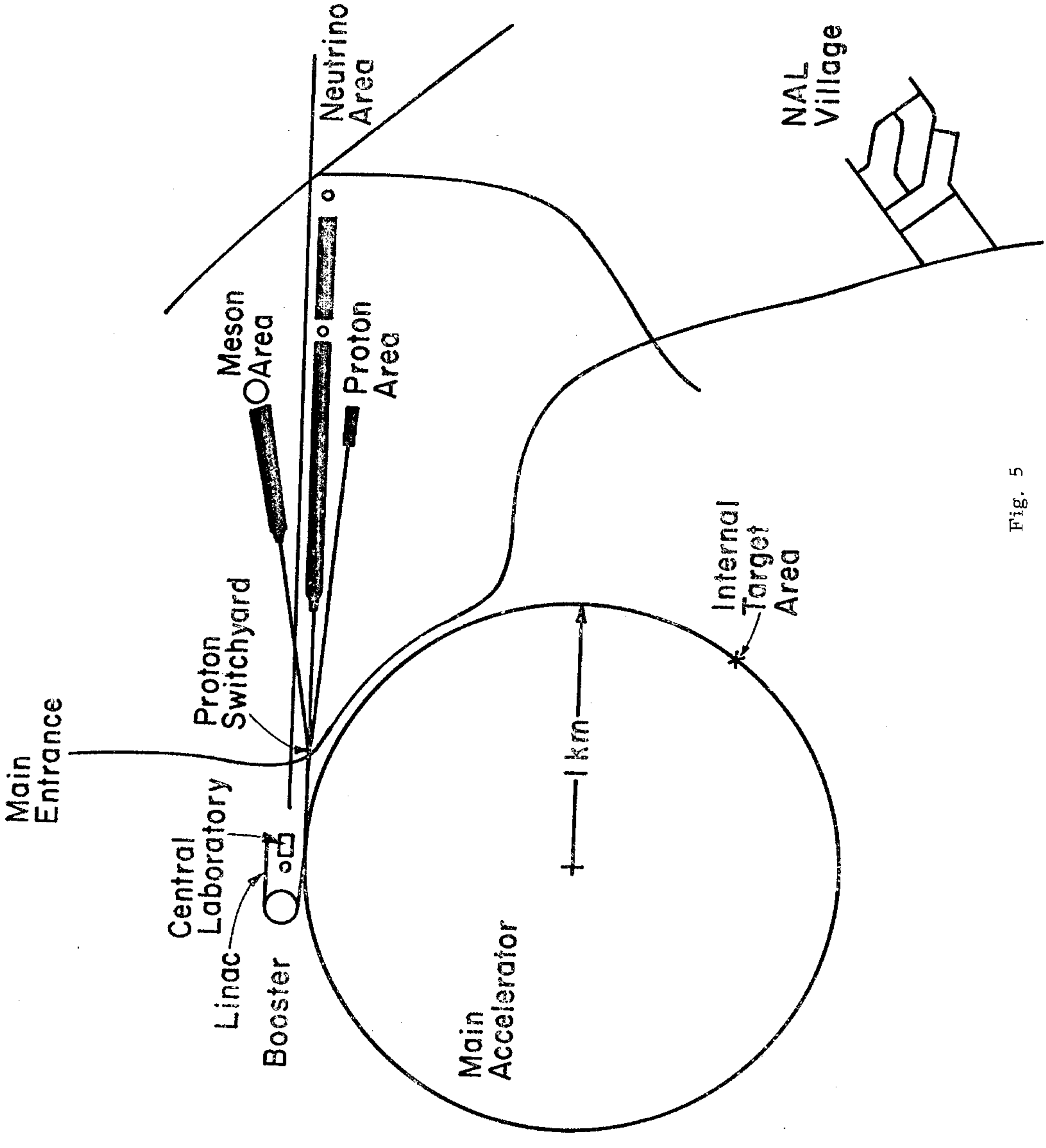
Main Entrance
Central Laboratory
Linac
Booster
Proton Switchyard
Meson Area
Proton Area
Neutrino Area
NAL Village
Internal Target Area
1 km
Main Accelerator

Fig. 5

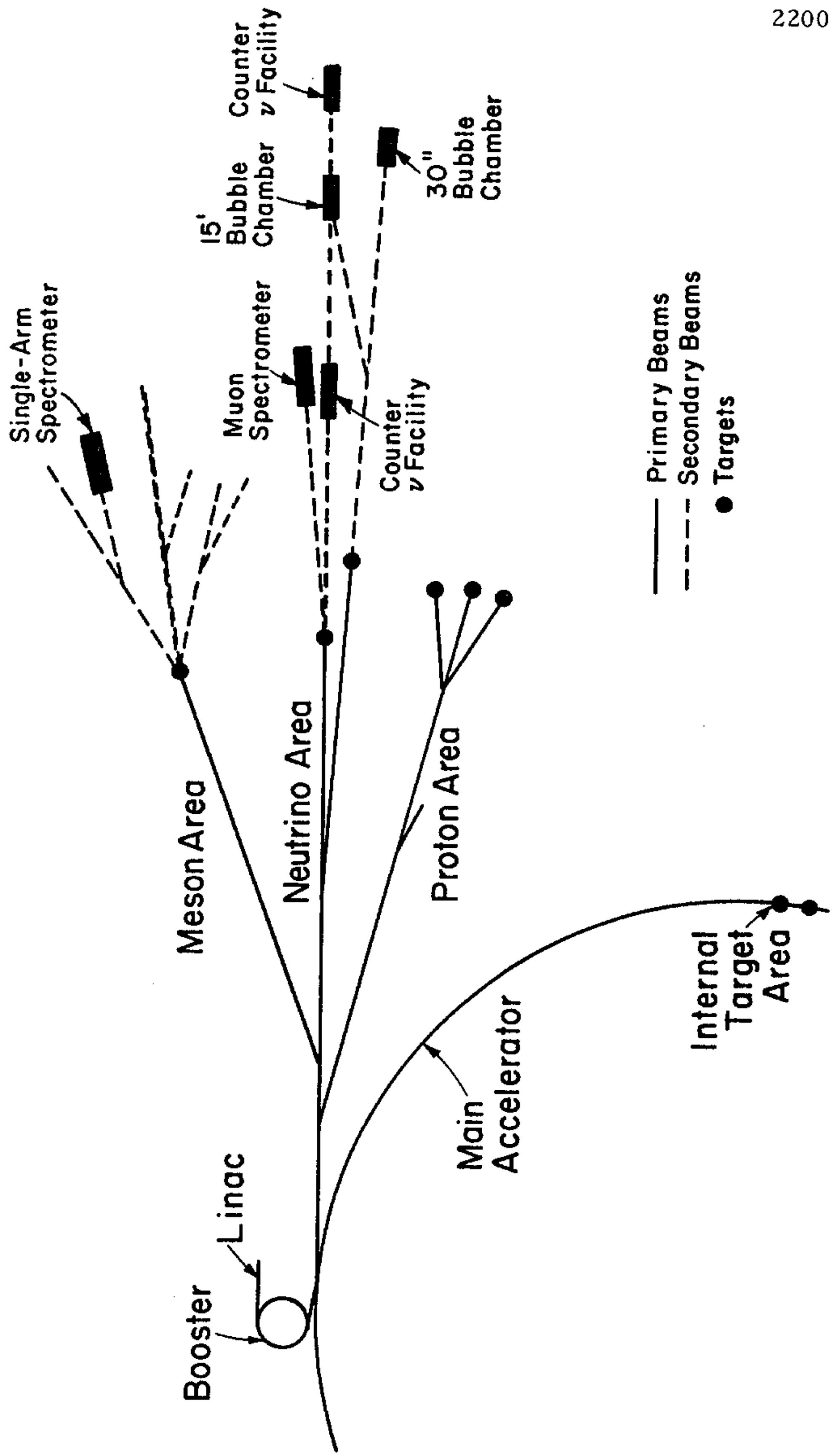
Counter
ν Facility
30"
Bubble
Chamber
15'
Bubble
Chamber
Single-Arm
Spectrometer
Muon
Spectrometer
Counter
ν Facility
Primary Beams
Secondary Beams
Targets
Meson Area
Neutrino Area
Proton Area
Internal
Target
Area
Main
Accelerator
Linac
Booster

Fig. 6